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Estimation of rock in-situ strength using Rock Strength Borehole Probe (RSBP)

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ABSTRACT: One of the main parameters that is commonly used for the rock mass characterization is the Uniaxial Compressive Strength (UCS) of the intact rock. This parameter is conventionally measured by diamond drilling to obtain core, and testing core samples in the laboratory, which is an expensive and time consuming process. It would be ideal if the strength of the intact rock could be estimated in the field as an in-situ measurement by running a device inside a borehole. Estimation of the rock strength by scratch tests has been reasonably accurate. Application of this concept for the assessment of rock strength in a borehole has led to development of a borehole strength measurement probe, namely Rock Strength Borehole Probe (RSBP). RSBP is designed to scratch the surface of rock with a miniature disc cutter inside a relatively slim borehole. The cutting forces are measured and used to estimate the rock strength. This paper discusses the background theories and experimental tests conducted for development of the RSBP, along with formulas developed for estimating the compressive and tensile strengths of the intact rocks. The RSBP probe and its components are briefly explained, and the observations from the initial field experiments with this probe are discussed in this paper.

1. INTRODUCTION

Good understanding of rock mass behavior is essential for engineering design of structures in rock mass and related geomechnical analyses. The proper use of rock mass models allows for obtaining meaningful outputs for safe design practices. One of the key properties of intact rock, which is widely used for assessment of rock mass properties and its behavior, is its compressive strength. Conventionally, rock strength is measured by testing core samples that are obtained from exploration boreholes or drilling into boulders collected from outcrops. Despite all the efforts and costs, the results may not necessarily show the behavior of the intact rock in the field since the test cannot provide the in-situ condition of the ground. Moreover, the tested samples are solely representative of few locations along the borehole. Moreover, there is always a time lag between the field work and the time where the results could become available for design purposes. Therefore, the ideal solution is to measure the rock strength in-situ, and preferably inside closely placed drill holes.

Achieving this goal was one of the main objectives of a study conducted at the Pennsylvania State University, as part of a project sponsored by National Institute of Occupational Safety and Health (NIOSH) mining and ground control group. This study aimed at developing a system for measuring rock properties while drilling for roof bolts. As such, there was a need to evaluate joints in the rock mass that was accomplished by using a borehole televiewer, and to estimate rock strength. While various approaches for in-situ estimation of rock strength was examined in the preliminary studies, it was concluded that none of the existing methods could work in a small, short, dry borehole.

Subsequently, it was decided to focus on developing a new method for in-situ estimation of rock strength to be used inside the boreholes drilled for installation of rock bolts. These boreholes are relatively small size (25.4 to 50.8 mm (1” to 2”) in diameter), and drilled in the roof and/or ribs of underground structures. Conventional methods for measuring rock strength inside boreholes have been developed for larger downward holes that are typically filled with water or other fluids. The new probe is specifically developed to work in upward boreholes that are not filled with water. The initial investigations indicated that the most suitable approach to design this probe based on, would be to use a mechanical tool for the measurement of rock strength. Using mechanical cutting concept allows for instantaneous measurements in the borehole.

Among the available concepts, scratch test method showed to be more promising and adaptable for the specific requirements of this application. This method requires minimum to no sample preparation. Also, the strength can be continuously recorded along the sample. It generates reliable outputs and can be applied on samples and intervals as short as couple of inches (Schei et al., 2000). Scratch test is based on the relationship between the rock cutting mechanisms, which links the cutting forces and mechanical properties of rock. This relationship has been extensively studied in past few decades (i.e. Fowell, 2013, Nishimatsu, 1993, etc.).

This paper will briefly explain the background of scratch test method, followed by discussing the results of the modified full-scale scratch tests performed for this study. Based on the preliminary results, new relationships have been developed between cutting depth and rock strength. These relationships will be used to translate the data recorded by the designed borehole probe into rock strength. The paper also reviews the designed Rock Strength Borehole Probe (RSBP) and its components. Finally, performance of RSBP in the laboratory and field trials will be discussed.

2. BACKGROUND

Scratch test was developed at University of Minnesota in 90's based on phenomenological model of cutter/rock interaction in the ductile regime for drag bits (Detournay and Defourny, 1992) and PDC cutters (Almenara and Detournay, 1992). In the ductile regime, the consumed energy is related to the volume of rock removed and as a result the strength of rock. The results of this study was incorporated to develop a device called "Rock Strength Device (RSD)" (Detournay et al., 1997), which was continuously improved over the years (Coudyzer et al., 2005). RSD, as shown in Figure 1, mainly consists of a frame, a load sensor, a driving motor and a data acquisition system. The range of force measurement is from 10 N to 4000 N, and is recorded with a resolution of about 1 Newton. The data acquisition rate is up to 1000 Hz (Richard et al., 1998) and the scanning rate is typically at 25 samples/mm (Richard et al., 2012). Its cutting system, sharp or blunt, accepts replaceable polycrystalline diamond cutters of 10 mm width and back-rake angle of 15° (Schei et al., 2000). Some companies, also, have developed their own devices with different names, i.e. profiler core scratch test system by Schlumberger (Schlumberger, 2014), and Wombat by Epslog SA (Mariano et al. 2011).

Scratch test is kinematically controlled, i.e. both the depth of cut and the cutter speed are maintained constant during the test. The depth of cut typically varies between 0.1 and 2 mm, while the cutter speed is usually set at a few mm/s, (e.g. 0.1 to 12 mm/s) (Richard et al. 1998). Both components of the force acting on the cutter are measured, i.e. drag force in the direction of cutter motion and normal force, which is perpendicular to the scratched surface. From the force measurements, the specific energy can be calculated (Schei et al. 2000). Richard et al. (2012) reported that more than 350 different rock samples, mainly sedimentary rocks, were tested by this method. This approach has attracted attentions in the oil industry to measure rock strength from the core samples retrieved from drilling operations (Peña, 2010) and recently has been the subject of studies to estimate fracture toughness (Akono and Ulm, 2014).

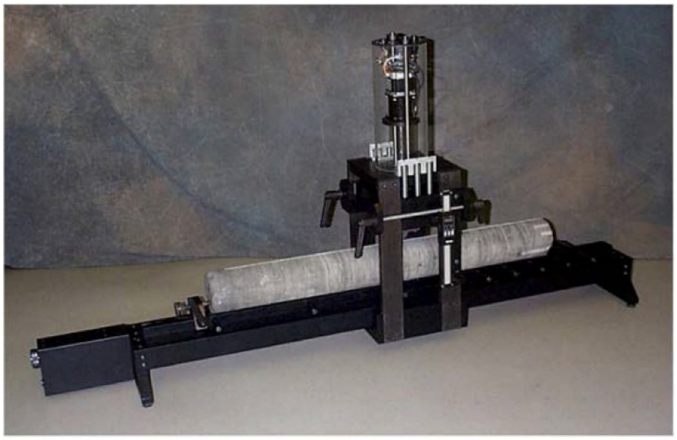


Fig. 1. Pictures of an early prototype of Rock Strength Device (RSD) (Schei et al., 2000).

3. FULL-SCALE SCRATCH TEST

In scratch test method, rock core retrieved from core drilling is used to estimate the rock strength. However, the aim of this study is to develop a method to measure the rock strength inside rock bolt holes to meet workflow in mining and tunneling applications. The new approach not only should be able to provide continuous strength measurements along the borehole, similar to the original scratch test method, but also to eliminate the need for coring. As a result, the idea of developing a new scratch probe has emerged. This probe will incorporate scratch test method to measure rock strength in-situ and inside closely drilled boreholes in underground openings. No sample preparation is needed for this method other than drilling boreholes, which is much faster than core drilling. These boreholes are often drilled during the normal operation cycle in tunnels or mines for roof bolting or blast rounds. Another advantage of this approach is that results can be readily obtained on site after performing the test by real time analysis of data using a specialized software.

To facilitate simple and easy use of the probe by an average operator and minimize the chance of the probe getting stuck inside boreholes, miniaturized disc cutters are selected to be used as scribes, instead of wedge shaped PDC that were used in the original scratch test. Disc cutters require higher normal force than drag type tools but takes less rolling (drag) force, thus making it easy to push the probe in a borehole and to retrieve it.

This means that additional scratch tests had to be conducted with miniaturized disc cutters to develop new correlations between the measured forces and rock strength. Therefore, a new full-scale scratch test device was designed and fabricated to perform these experiments, as shown in Figure 2. Precise instruments and load sensing components were used to assemble this device to meet the required high accuracy. A triaxial load cell with about 14000 N or 1360 kgf (3000 Ibs) capacity measures the cutting forces in three directions. The load cell data is recorded by a NI USB-6341 X series data acquisition system (DAQ). A readout system also shows the position of the cutting tool in X, Y, Z directions with the accuracy of 0.0001 mm as well as its velocity. A special flat PDC bit was used to precisely level the surface of the sample.

The scratch tests were performed on various samples ranging from soft (coal), medium strength (e.g. limestone), to hard rocks (granite). Some of the samples were collected from the nearby coal/limestone mines in Pennsylvania, USA but majority of the samples were obtained from quarry mines around the world. Samples can be categorized as i) sedimentary, such as limestone, siltstone and conglomerate, ii) metamorphic, e.g. marbles, travertines, and iii) igneous, like granite. Other than strength and type of formation, the samples had a range of grain sizes from fine to coarse. These samples were tested by standard rock mechanics methods before running cutting tests. This includes Uniaxial Compressive Strength (UCS) and Brazilian Tensile Strength (BTS).

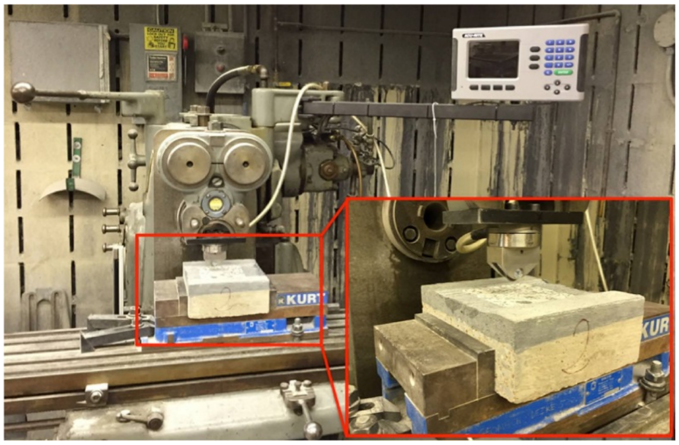


Fig. 2. Normal force vs. penetration depth for metamorphic rock samples.

The rock samples were cast in concrete to provide confinement for the test specimen. Each test, at prescribed specific penetration and speed, was repeated at least 3 times for most of the rock samples. During the scratch tests, the cutting velocity was kept constant. Since the operation of the probe is manual and therefore probing would most likely happen in non-constant speeds, a number of samples were tested under five different cutting speeds, i.e. ~2, 8.3, 25, 42, 50 mm/sec (4.5, 20, 60, 100 and 120 inch/min) to observe the impacts of cutting speed. In this study, cutting depth varied between 0.2 mm and 1 mm with an interval of 0.2 mm. In order to minimize the effect of the adjacent scratches, a distance or cut spacing of 10 mm was maintained. Negligible to no bit wear was observed after making scratches on the surface of two limestones, an igneous rock, a travertine and a marble sample. However, the disc cutters were replaced occasionally to eliminate any possible wear effect on the results. Figure 3 shows the typical result of cutting test and the change of cutting forces in X, Y and Z directions at the depth of 0.6 mm on a limestone sample.

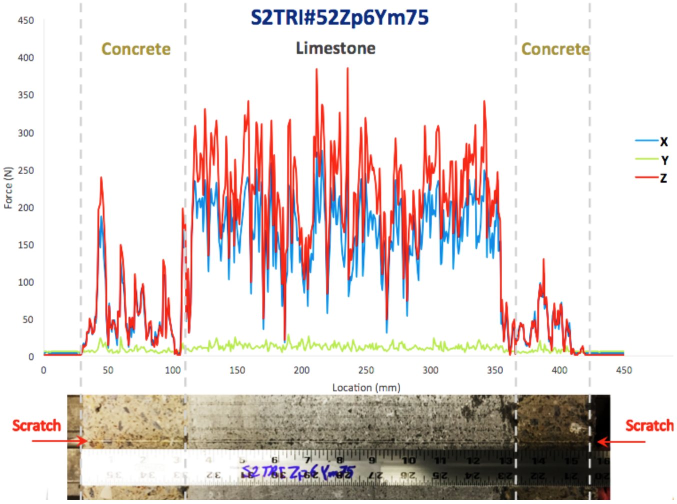


Fig. 3. Typical result of cutting test and the picture of the cut on the sample surface.

More than 600 tests have been completed on different rock samples with different strengths and structures. For each test, the representative rock signature window was manually selected and then the average of normal and rolling forces within that range were calculated using a code developed in MATLAB. The results for each penetration depth were subsequently evaluated and the outliers were discarded. In the next step, the average of normal and rolling forces were calculated for each penetration depth. Figure 4 shows the measured normal forces at various depth of penetration for metamorphic rock samples. This chart indicates the existence of linear correlations between the measured normal forces and penetration with good R-square values. Similar correlations were found for other types of rocks and also rolling forces.

The correlations between UCS and the measured normal and rolling forces were also investigated. Igneous rocks did not show any noticeable correlation between UCS and normal force values, while the sedimentary and metamorphic rocks showed a good linear trend. As a result, igneous rocks were not included in further analyses.

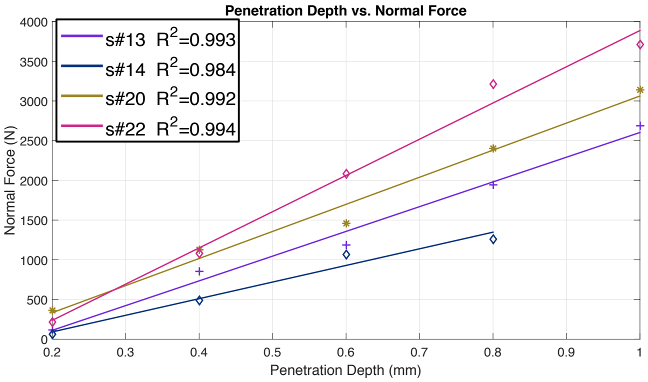
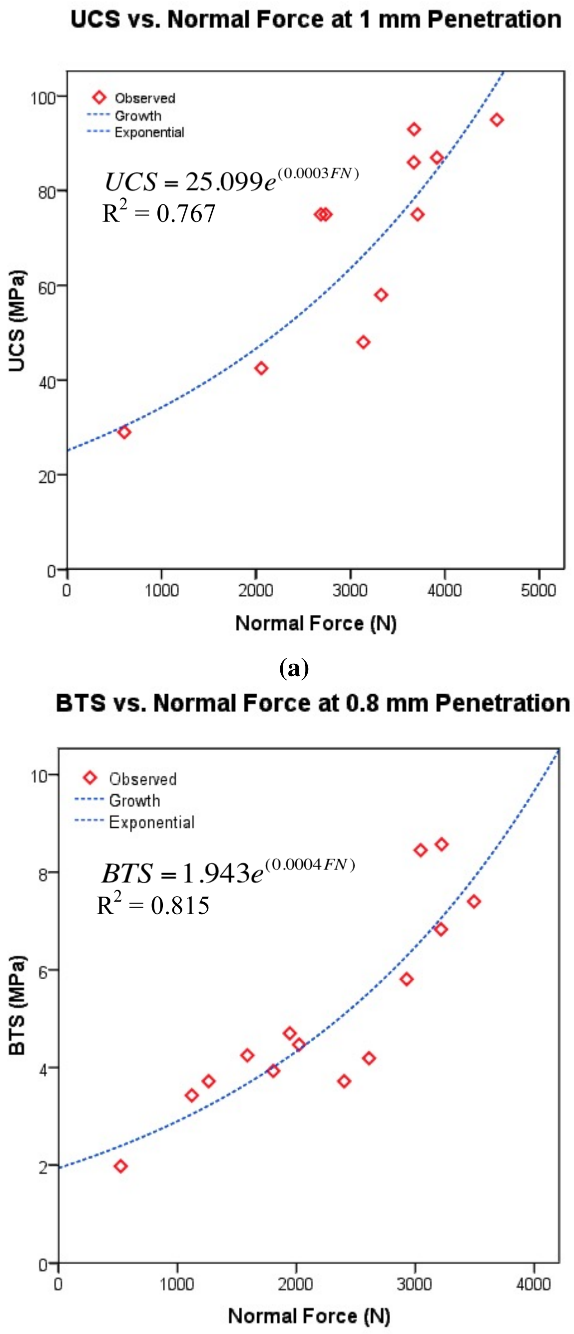


Fig. 4. Normal force vs. penetration depth for metamorphic rock samples.

For sedimentary and metamorphic rocks, statistical analysis was conducted using SPSS software to examine the correlation between normal and rolling forces, and both UCS and BTS values, at each penetration depth. In most cases, exponential function offered the best fit and the data from 8-mm deep scratch tests gave the highest R-square, in majority of cases. Normal and rolling forces both gave acceptable formula for the sedimentary and metamorphic rocks. The graphs in Figure 5a and b show the best fits and their formulas for UCS and BTS of sedimentary/metamorphic rocks, respectively. It should be mentioned that although these results are from a broad range of rock types, more rock samples need to be tested to verify these outcomes.

4. ROCK STRENGTH BOREHOLE PROBE

As mentioned earlier, the results of cutting tests was used for the design of Rock Strength Borehole Probe (RSBP) to accommodate quick measurement of rock strength from a small borehole. The probe is designed to be 38.1 mm (1.5”) in diameter, which allows it to be operated inside boreholes with 44.5-51 mm (1.75-2”) diameter. These boreholes can be 2 to 10 m (7-30 ft) long. The manufactured probe is designed to be user-friendly and is light enough for an average person to operate. This probe will measure normal and rolling forces on the scribe with a load sensing device, and monitors linear displacement using optical sensors and a micro controller. All the data can be stored on a SD card for subsequent analysis. Figure 6 shows the initial conceptual design of the RSBP. At the initial design stage, a depth sensor was considered to be employed to continuously record the depth of the generated scratch. However, further investigations showed that currently no sensor is available with suitable dimensions that is cost effective and has sufficient accuracy.



(a)

(b)

Fig. 5. Best curve fits and their formulas for (a) UCS, and (b) BTS, of sedimentary and metamorphic rocks.

In this probe, the scribe is pressed against the borehole wall by two sets of spring-loaded guide wheels located on the opposite side of the scribe. In addition, two smaller wheels are attached to the ends of the cutter housing in order to limit the depth of the cut. The combination of these four guide wheels will help ensure that the scratch depth is maintained constant while RSBP is running along the hole, without imposing excess pressure on the cutter housing and therefore the strain gauges. In the following sections, different parts of this probe are explained in more details.

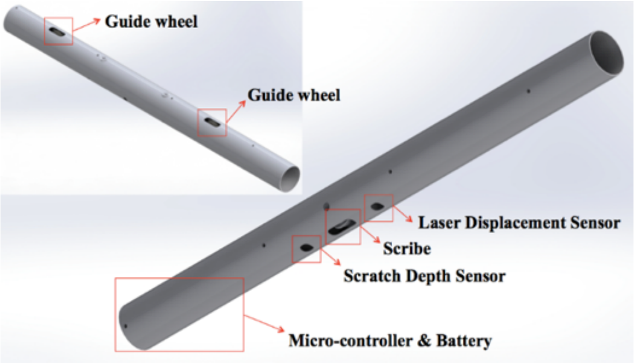
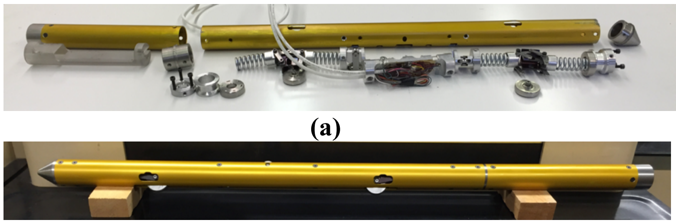


Fig. 6. The conceptual design for the mechanical part of scratch probe with a disc scribe.

4.1. *Mechanical parts*

The mechanical parts of the probe were designed using SolidWorks, which went through many design iterations and modifications. Most of the mechanical parts are fabricated from 6061 Aluminum. This alloy is corrosion resistant, relatively light and strong. Despite this fact, some of the more delicate parts were also heat-treated to increase their load bearing capacity and surface hardness. All the components are assembled and fit inside an anodized Aluminum tubing. Figure 7 (a) and (b) show the components of the designed probe and the final product, respectively.



(a)

(b)

Fig. 7. RSBP (a) before, and (b) after the final assembly.

The main mechanical part of the probe is the cutter housing. A number of concepts were evaluated for the cutting mechanism from different aspects, individually and in combination with other components. Also, during the manufacturing some adjustment were made to make the assembly process easier. Figure 8 shows the schematic design of the main sensor.

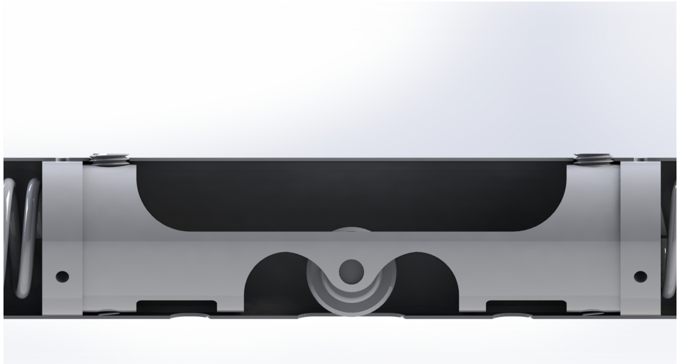


Fig. 8. Close-up view of the cutting housing.

4.2. *Electrical parts*

For the electronic assembly of the probe, a circuit schematic was generated. In this design, the Teensy 3.2 microcontroller is the key component and works as the brain part of RSBP. This item interfaces with the laser sensor, strain gauge, SD card module, and time clock module. Teensy 3.2 has a suitable size and is rated at 72 MHz with a SPI communication bus, which is needed to interface with the laser sensors and SD module. It also has a storage and RAM of 256 KB and 64 KB, respectively, and the speed meets the required data acquisition rate as well. The SD card module will record the received data from the microcontroller on a MicroSD card. This module transfers data at the rate of 50 MB/sec with 4 parallel data lines and is compatible with cards that have up to 16 GB of memory. Two other main electronic components are the strain gages and the position laser sensor. These components are installed inside the cutter housing section. The forces are measured by strain gage systems with eight strain gages attached to the upper surface of the cutter housing. This system is self-adjusting for changes in temperature and will allow the probe to measure normal and rolling forces.

For the measurement of the probe position inside the drillhole, laser sensors were deemed to be the most accurate. The laser sensor selected for this project is very small, low cost and has the right resolution and precision to fit this application. The lens can be adjusted to a maximum distance of 5mm. The resolution is also adjustable to different surfaces. This sensor measures changes in position by optically acquiring sequential surface images (frames) and mathematically determining the direction and magnitude of movement. Based on the initial test results, the x-direction of the sensor was found to produce more accurate data and as a result, the sensor was installed accordingly on the probe. These tests also showed that the sensor can measure the position with a systematic error of less than 10% for dark color rocks under different brightness conditions.

The probe relies heavily on an efficient software system in order to collect the physical inputs and produce accurate outputs in an easy-to-read format. The code is written by Arduino software, and is developed in a way that all the data is recorded on a micro SD card every 500 ms to maximize the battery life. This code has been progressively improved and optimized so that the sensors are reliably interfaced with the Teensy microcontroller.

Other than strain gauges and the position sensor, all the other electronics were installed inside a polycarbonate electrical housing. This housing consists of three main sections which are SD Module fixture, battery holder and the printed circuit board platform, as illustrated in Figure 9.

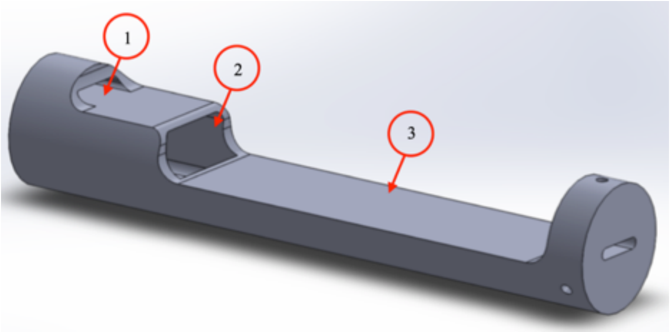


Fig. 9. Electrical housing 3D model, where (1) SD Module fixture; (2) 9V-battery holder; (3) PCB platform.

5. RSBP LABORATORY AND FIELD TESTS

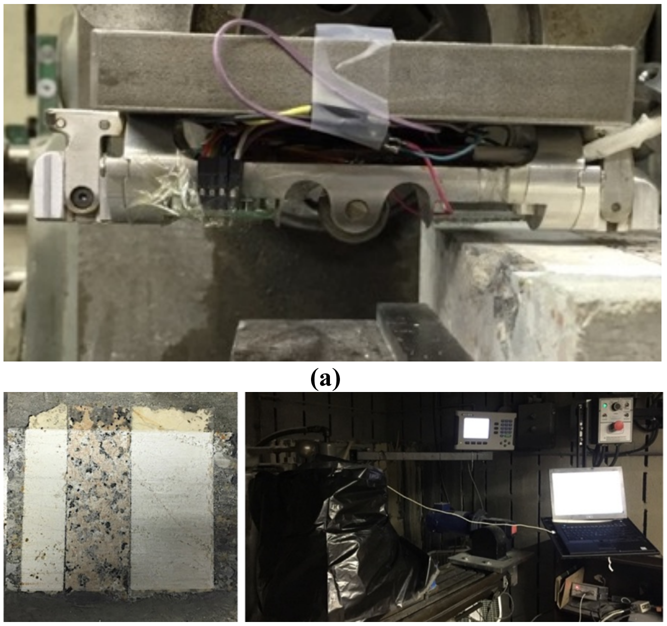
In this section, laboratory and field tests that have been conducted on RSBP device are explained.

5.1. Laboratory tests

After full assembly of the prototype probe, various experiments were conducted on different components of RSBP to assess the performance of each individual part as well as the whole device. Two of the main laboratory experiments, "Sandwiched rock sample" and "mine roof simulation", are presented below. The objective of the first series of tests was to evaluate the interaction between sensory components and to ensure that the electronic components work properly and can reliably collect/record useful data. The second experiment, however, was focused on assessing the performance of fully assembled RSBP in an underground simulated environment.

For "Sandwiched rock sample" test series, the actual cutter housing was mounted on the developed miniature linear cutting machine that was used for the performance of aforementioned scratch tests. These tests involved cutting of a sandwich of selected rock samples fabricated to simulate the rock layers inside a borehole. The test procedure was similar to the previous scratch tests, except that the data was recorded on the micro SD card, and the testing area was covered with a black plastic sheet to simulate the darkness inside the borehole. Figure 10 (a), (b), and (c) show the cutter housing assembly, the fabricated sample, and the test setup, respectively.

The selected rock samples for this experiment included (from left to right in figure 10 (b)) travertine (S25), pegmatite (S6), and limestone (S18). UCS values of the samples were measured at 58, 134, and 93 MPa, respectively. The tests were performed for the penetration depths of 0.6 and 1 mm with three repetitions for each test. Figure 11 depicts a typical result for the test with a scratch depth of 1 mm. The plot shows both front and rear strain gauge bridge outcomes in mV, as well as the position of the scribe in millimetres and inches. Moreover, the plot is divided into five sections, which shows the location/span of each rock sample or concrete, and the black lines in each window approximate the transition between rocks. As expected, limestone shows the highest mean value, and the travertine has the lowest force reading. Although pegmatite has the highest strength from the scratch test results, a medium intensity of measured forces was observed due to the texture of the rock and its dependence to mineral grain size.



(a)

(b) **(c)**

Fig. 10. (a) cutting housing assembly, (b) the fabricated sample, and (3) the test setup developed for sandwich rock sample experiment.

The initial analysis of data shows acceptable performance of both strain gauges and the laser sensor. Moreover, all the experimental data were successfully recorded on the micro SD card, which means that the electrical components interact well together. However, more tests need to be run to calibrate the system for working conditions that could be encountered in a borehole.

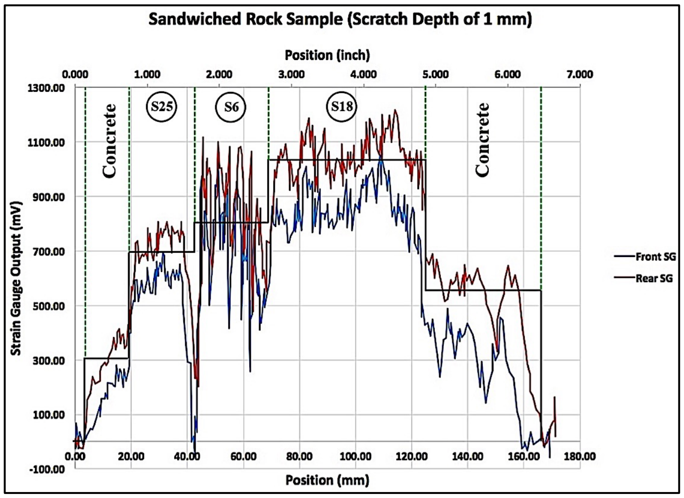


Fig. 11. Typical test result from the sandwich rock sample experiment.

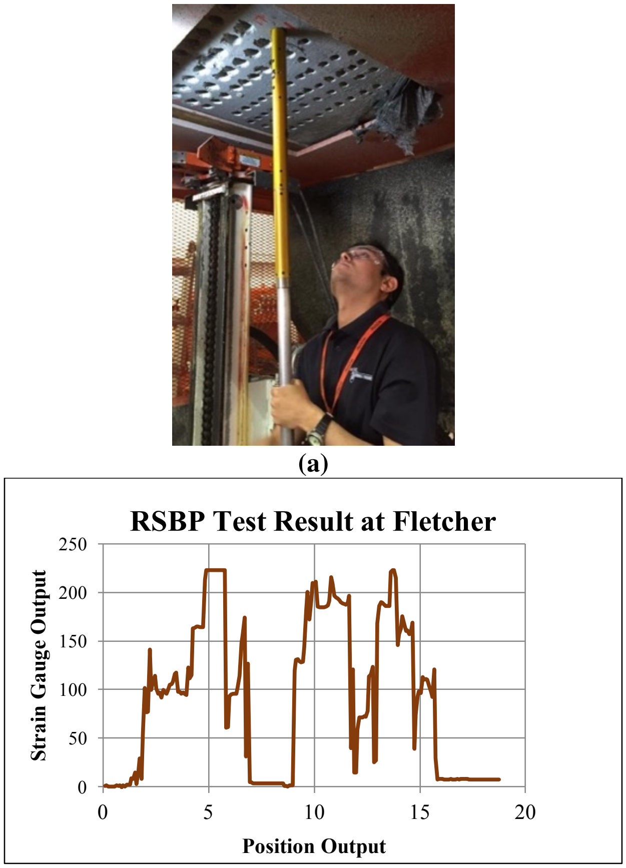
After observation of acceptable results from the sensory parts, the RSBP was fully assembled to be tested at

J.H. Fletcher & Co testing facility in Huntington West Virginia. For these experiments, a cast concrete block was fixed at the top of the drilling rig platform, and several upward holes were drilled into the designated block, as shown in Figure 12 (a). The tests proved that the RSBP operation can considerably be affected by waviness of the borehole surface. Despite the considerable undulation of the walls along the holes, some successful tests were run. Figure 12 (b) presents raw outputs from one of the tested boreholes.

The experiment, in general, showed that all of the electronic sub-systems were working well, and the mechanical parts was able to scratch the surface of borehole, which means that the tool was ready for field testing.

5.2. Field tests

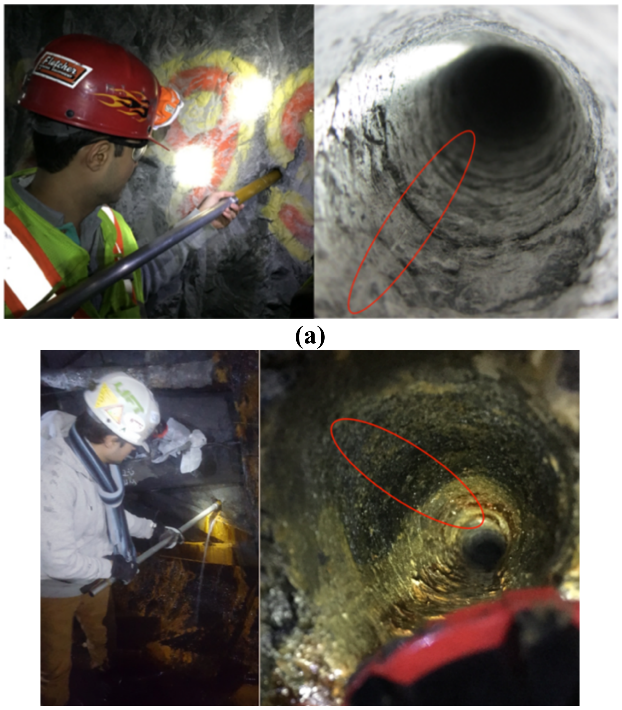
RSBP was tested in two stages at two underground mines. In the first stage, the mechanical performance of the probe was examined at a limestone and an anthracite coal mine. In these field tests, a number of sub-horizontal and sub-vertical boreholes were probed. The boreholes were then examined visually and in some cases by a borescope. Figure 13 (a) and (b) shows the condition of boreholes after the testing and typical scratch traces that were generated by running RSBP inside the borehole in the limestone and coal mine, respectively.



(a)

(b)

Fig. 12. (a) probing the holes drilled into a concrete block at J.H. Fletcher & Co. facility; (b) Typical test result obtained from this series of probing.



(a)

(b)

Fig. 13. Testing RSBP mechanical performance at (a) a limestone and, (b) anthracite coal mines and the image of generated scratches inside the boreholes.

The follow up work involved testing the performance of the overall probe at Graymont underground limestone mine. The graph in Figure 14 depicts the result for one of the tested boreholes. This graph shows the strain gauge outputs from where the laser sensor has started to register data up to where the probe has reached the maximum depth, which is about 1500 mm (60 inches). From this graph and the field observations, it can be concluded that both guide wheels got fully engaged at about 250 mm (10 inches) from the collar of the borehole. Moreover, the sudden plunge at the depth of about 750 mm (30 inches) might be due to a wide discontinuity. Variation of forces in this graph is fairly constant, which suggests that only one type of rock with the same strength along the borehole was encountered.

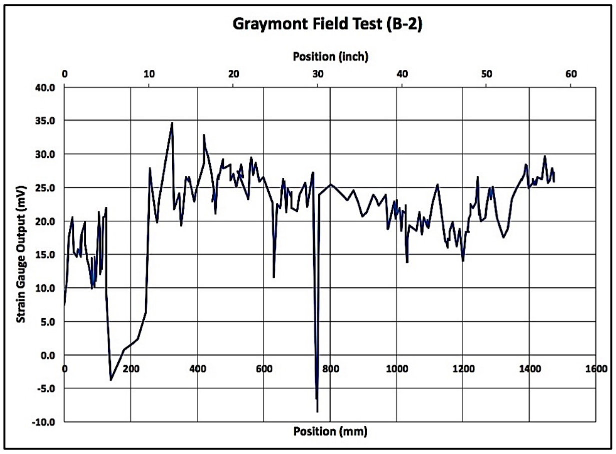


Fig. 14. Experiment The result of probing a borehole by RSBP at a limestone mine.

6. CONCLUSION

Scratch test concept was used for developing a new borehole strength probe, which is designed to estimate rock strength inside small boreholes by scratching their wall using a disc-shape scribe. These small boreholes are commonly drilled in tunneling/mining operations for rock bolt installation or blast rounds. In order to be able to translate scratching forces from the probe into rock strength, many scratch tests were performed. The results of these experiments showed that good correlations can be found between cutting forces and the intact rock strength properties of sedimentary and metamorphic rocks. No significant correlation was found for igneous rocks, perhaps due to heterogeneous nature of these rocks based on the various grain size and rock texture. For sedimentary and metamorphic rock samples, formulas with R-square of about 80% were found for the estimation of UCS and BTS, respectively.

Based on these new scratch tests, rock strength probe was designed and fabricated. The laboratory and field tests proved that the mechanical and electronic components of this tool can work together and are able to record the force and position data. Additional field tests are underway to evaluate performance of the probe under various working conditions. Also, more laboratory tests are required to calibrate the force and position measurement systems.

7. ACKNOWLEDGMENT

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